The removal of urban litter from stormwater conduits and streams: Paper 2 - Model studies of potential trapping structures

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Abstract

A large quantity of urban litter is finding its way into the drainage systems to become an eyesore and a potential health hazard. Although much effort has been expended on the development of trapping devices, most of the traps currently installed are extremely ineffective at trapping and storing urban litter. There was thus a pressing need for a physical model study into the design of litter traps. Such a study was carried out in the hydraulic laboratories at the Universities of Cape Town and Stellenbosch. It clearly showed why most designs fail, and clearly identified the use of declined screens as an approach that holds considerable promise for the future. The findings broadly concur with the results of a similar model study that was recently carried out in Australia.

Introduction

Urban litter, defined as visible solid waste emanating from the urban environment (Armitage et al. 1998), and henceforth called simply "litter", is extremely difficult to trap and remove once it has entered the drainage system. Although much effort has been expended on the development of trapping devices, most of the traps currently installed are extremely ineffective at trapping and storing urban litter.

It is thus clear that there is a need for an inexpensive, reliable, effective trapping structure which ideally has no moving parts, is robust, is vandal-proof, does not require an external power source, is easy to clean (preferably self-cleaning) and does not increase flood levels in the vicinity of the structure. This clearly excludes the standard screens and de-gritting devices commonly found at wastewater treatment works. It also excludes the standard trash-racks comprising vertical or near vertical bars commonly found across river off-takes. With no surplus flow to scour them, these racks rapidly block from the bottom upwards. With this objective in mind, numerous candidate model structures were constructed and tested in the hydraulic laboratories at the Universities of Stellenbosch and Cape Town.

The tests conducted may be conveniently divided into two groups. Initially the investigation was mainly focused on screenless traps, or traps with a limited penetration into the water column (if the screen blocked, stormwater would still be able to pass the structure with limited upstream flooding). As it became apparent that screenless or limited screen traps were not efficient in the majority of applications, the focus of the investigation was switched to "self-cleaning" screens. The traps were generally conceived as structures capable of screening the relatively high flows to be expected at some point downstream of a fairly extensive urban catchment.

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Received 23 July 1999; accepted in revised form 22 December 1999.

Experimental method

For each model, water was supplied from a constant-head tank to a point upstream of the model structure, excessive vorticity was eliminated by passing the flow through a small reservoir and/or flow straighteners (usually in the form of bundled pipes), litter was added to the flow, the flow was passed through the structure, litter that was not trapped was removed by means of a downstream screen, and the water was re-circulated to the constant head tank. The flow was either measured with the aid of an orifice plate in the supply pipe from the constant head tank, or by the insertion of a weir (usually a V-notch) in the channel.

The width of the inflow/outflow channel was different for each model and varied from 280 mm to 900 mm. The nominal scale (which was required for the purpose of relating litter size, litter settling velocity, flow rate, length, depth and slope to prototype structures) was also different for each model, and varied from 1:25 for the smallest models to full scale for the largest.

Plastic chips were generally used to represent litter. Different litter fractions could be modelled by choosing plastic chips of different sizes and settling velocities (related to the shape and density of the chips). In the case of the full-scale model, polyethylene shopping bags were used as the representative litter fraction, as previous experience, both in the laboratory and in the field, had shown that these bags are simultaneously the largest single litter fraction (up to 60% of the litter load) and the hardest to trap (Armitage et al., 1998). The trap efficiency of each structure at each flow rate was expressed as the litter fraction trapped divided by the amount of litter released. These quantities were measured by counting the individual items, weighing the litter, or measuring its volume - whichever was most appropriate for the particular test. Particular care had to be taken where litter was weighed or its volume measured, as the results were easily distorted by water and/or air bound up with the particles.

Screenless and partial penetration screen traps

One approach was to reduce the transporting capacity of the flow by lowering the average velocity to a point where the suspended material divided into flotsam and bed-load material which could be separated by means of suspended baffle walls and weirs respectively. Several attempts were made to design a trap that caught litter in this manner

Uys, 1994

In an attempt to save as much space as possible, Uys split the flow in two around the separation structure, and then turned the two streams inwards through almost 90° from the oncoming flow direction to pass under several baffle walls. A low weir in the downstream channel ensured that the opening under the baffle-wall was always under water (Fig. 1).

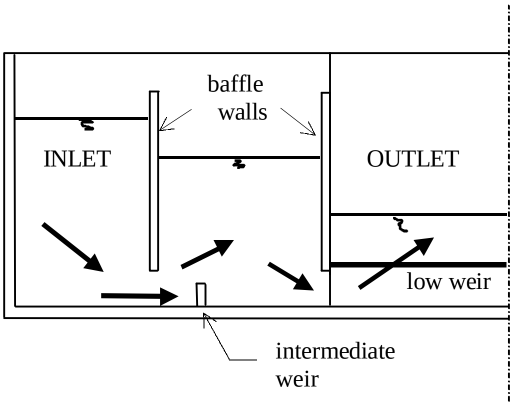

Figure 1
Half-section through the Uys trap

Although the structure seemed to show considerable promise whilst the flow rate was reasonably low, as soon as the flow rate increased above a certain critical value, the increased vorticity re-entrained the scaled litter particles and passed them through the trap and into the downstream canal. Some improvement in retention was achieved by the addition of a second baffle-wall and an intermediate weir on either side of the structure, but in general the trap was a failure.

Wilsenach, 1994

In the Wilsenach structure, longitudinal slots were located at approximately mid-height along both walls of the inflow channel. This channel ended with a blank wall. The hope was that the bed-load and flotsam would be desegregated as a result of the reducing velocity in the central channel and be trapped there. The slots would then allow the relatively litter-free mid-depth water out of the inflow channel into outflow channels constructed on either side of, and parallel to the inflow section. A downstream weir would keep the water depth in the inflow channel within narrow limits (Fig. 2).

Problems were immediately encountered with vorticity in the inflow section as a result of the torturous path the water had to follow through the slots and into the side-channels. The vorticity was particularly severe in the vicinity of the stop-end. The addition of flow deflectors, flow straighteners and a second weir parallel to the flow direction helped to improve the performance of the trap, but the result was an extremely complicated structure. Once again the trap was considered a failure.

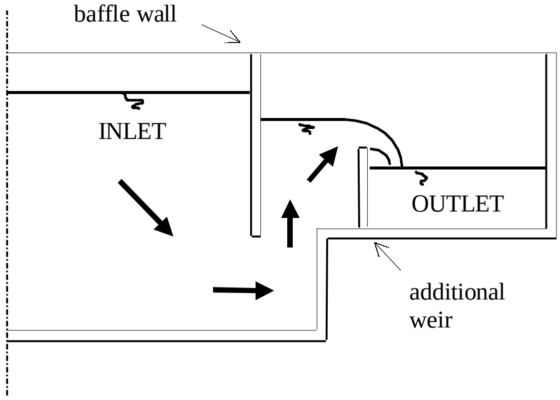

Figure 2
Half-section through the Wilsenach trap (straighteners not shown)

Furlong, 1995

The failure of the Uys and Wilsenach investigations now prompted some fundamental research into the limitations of suspended baffle walls as a method of removing flotsam.

A single suspended baffle wall was shown to be almost completely ineffective at trapping flotsam (Fig. 3(a)). Except at extremely low flow rates, almost all the litter followed the streamlines (indicated by the addition of vegetable dye) and was pulled under the baffle wall. Frequently, more litter was trapped in the vortex downstream of the baffle wall than was trapped upstream of the baffle!

Double baffle walls either acted as though they were one (if they were close together), or like two separate baffle walls (if they were further apart). There did not appear to be any benefit in using double baffle walls.

When a single suspended baffle wall was used in conjunction with a horizontal shelf suspended above the bottom of the channel in the upstream direction (Fig. 3(b)), the combined structure behaved almost exactly as though the shelf was not there and the litter passed beneath the baffle.

When, however, the solid shelf was replaced with a screen, provided the litter was floating above the line of the screen immediately upstream of the trap, it was generally trapped. Very good packing was achieved in the area above the screen, the capacity of which appeared to be only limited by its length. It appeared that there was almost always sufficient draught through the previously deposited litter to ensure that later deposits were overlaid in an efficient manner. The biggest shortcoming with this structure appeared to be the fact that in the event of intensive vorticity upstream of the trap, the litter particles tended to move closer to the bottom of the flume and consequently pass underneath. Inclining the screen improved velocity head recovery (Fig. 3(c)).

Louw, 1995

The purpose of this investigation was to explore the possibility of using an inclined suspended screen in association with a long length of weir to trap the flotsam and bed-load respectively.

The average flow velocity was reduced by expanding the canal section as well as through the damming effect of the weir. This, it was hoped, would induce the necessary desegregation. To reduce the size of the structure, the weir was constructed in the form of a 'V', with the apex pointing upstream. At the same time, the expanded section was brought uniformly back to that of the original

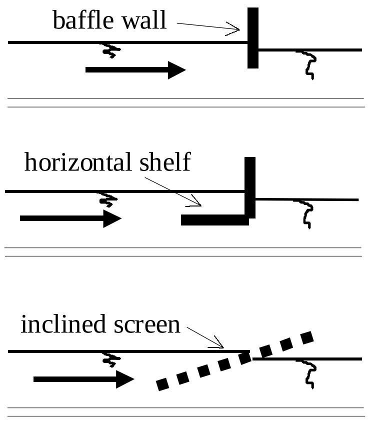

Figure 3
The Furlong experiments (long-sections)

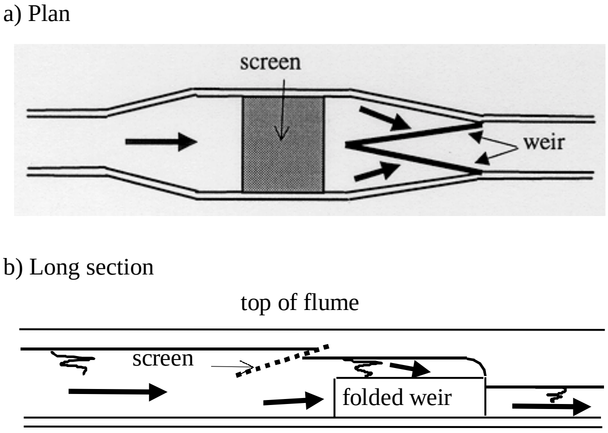

Figure 4
The Louw trap: plan and long-section

canal over the length of the weir. The uniformly reducing section coupled with the relatively uniform overflow rate over the weir guaranteed that the "forward" velocity was also more or less constant. The long overflow length guaranteed that the vertical velocity component was fairly small and also more or less constant. No attempt was made at this stage, with the small-scale model that was used, to study the effect of the addition of the screen (Fig. 4).

The initial test results seemed very encouraging as particles with widely differing settling velocities were trapped behind the weir over a wide range of flows.

Burger and Beeslaar, 1996

A key to the success of the Louw structure was the efficiency of the suspended inclined screen in trapping the majority of the flotsam and suspended material. This was now assessed by carrying out measurements with a screen inclined at an angle of 1:5 (vertical : horizontal) to the upstream flow direction (Fig. 5).

The tests indicated that an effective screen opening, a/w, of 0.5 resulted in a relatively high trap efficiency, but this was associated with a relatively high head loss. If a/w $\geq$0.6 the head loss across the structure decreased, but so did the trap efficiency. An effective screen opening of 0.5 at the design flow appeared to be the practical lower limit for a partial screening structure if the risk of upstream flooding was to be minimised.

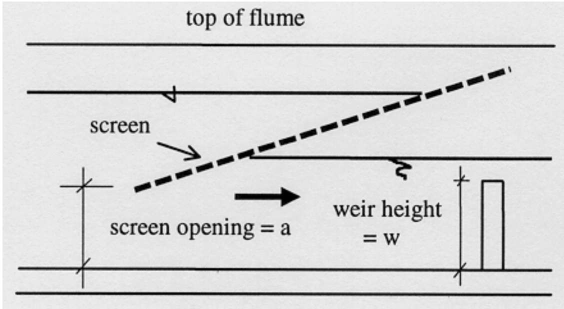

Figure 5
Long-section through the suspended inclined screen experiment

Compion, 1997 (Part 1)

The relative success of the Louw structure (see Fig. 4) prompted an in-depth investigation at a larger scale. Tests were carried out for a variety of flow rates and weir heights for a uniform channel without expansion, and a channel expanded to twice its normal width. Tests were also carried out with the apex of the folded weir pointing both upstream and downstream, and finally, in the case of the expanded channel, with weirs having both single and double folds.

With a single folded weir pointing upstream in a uniform channel without a screen in position using particles with a settling velocity of 27 mm/s (to represent litter with a positive settling velocity), the performance of the trap was almost independent of the channel width to weir height ratio. Complete trapping was only achieved when the Froude No (Fr) dropped below about 0.05. If Fr exceeded 0.30, no particles were trapped. Turning the weir around resulted in a decline in trapping performance.

Expanding the channel to twice its initial width was expected to improve the trapping performance since the average velocity would be approximately halved. However, the large vortices generated at the diverging section ensured that a considerable number of particles were kept suspended by the flow and washed over the weir.

When the screen was installed, there was a major deterioration in the performance of all the layouts. It had now become obvious that the vorticity associated with any obstruction such as an expansion, baffle or screen tends to result in the suspension and carry-over of particles. If partially penetrating screens were to be used in conjunction with weirs, they would have to be kept a substantial distance upstream of the weir.

Self-cleaning screens

As it became increasingly clear that screenless and partial penetration screen traps were not practicable in the majority of stormwater applications, attention was increasingly focused onto "self-cleaning" screens.

Visagie, 1994

This layout was investigated as a consequence of problems that Cape Town City Council had had with a litter trap that they built on the Vygekraal Canal in Athlone Park. A screen, comprising a series of overlapping horizontal rods cantilevering from vertical posts, had been positioned in the canal at an angle of 11° to the flow direction. The designer had anticipated that the litter would be deflected along the screen until it came to the canal wall. A 10 m diameter circular "sump" was constructed next to the canal in line

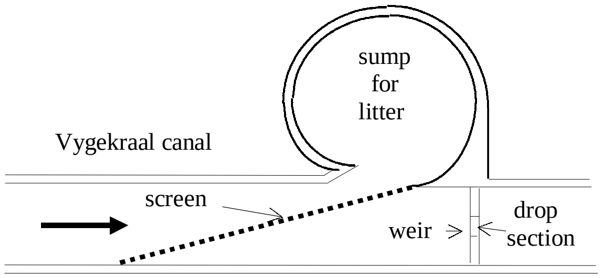

Figure 6
Plan of the Vygekraal Canal trap

with the screen to trap the litter (Fig. 6).

Once installed, it was readily apparent that the designer was mistaken and that the litter tended to stick onto the screen - particularly at low flows. The grating only deflected litter at high flows if there was no initial accumulation on the screens. Once deposition on the screens began, the flow direction was affected and the accumulation rapidly increased.

Visagie (1994) clearly showed that the performance of the structure could be improved by the construction of a low weir a short distance downstream of the screen. The effect of this weir was to reduce the average flow velocity through the screen - particularly at low flows. This reduced the head loss across the screen, which in turn reduced the tendency for litter to be pinned against it giving it more opportunity to drift into the sump. The higher the weir the better, as this reduced the average flow velocity still further, but of course this also increased the danger of upstream flooding. The shape of the weir was also shown to be important. Better results were obtained when the flow was concentrated down the centre of the canal by means of a central drop-section.

The structure was shown to be particularly vulnerable to large concentrations of litter coming down the canal. In this instance the litter tended to clump together against the screen, or between the downstream end of the screen and the canal wall.

Compion, 1997 (Part 2)

After failing to improve on the Louw structure (described above), Compion then attempted the development of an in-line, horizontal, self-cleaning screen.

Flow in a 600 mm channel was forced through critical depth over a 100 mm high broad-crested weir. Once over the weir, the flow was directed down a spillway section consisting of a ramp at a uniform 1:10 slope. A horizontal screen, comprising 5 mm wide bars with 10 mm openings orientated in the downstream direction, was placed at the same level as the top of the weir, and connected to it. Compion anticipated that litter would be separated from the flow by the screen whilst the momentum of the water flow would continually push the litter along the bars and out of the way. The ramp was intended to fulfil two purposes - to maintain a large momentum component in the plane of the horizontal screen (approximately 99.5% of the total at the angle chosen), and help minimise local head losses. At the toe of the ramp, the section was abruptly expanded to twice its original width, whilst the horizontal bar screen gave way to a grid sloped at an angle of 25° above the horizontal over the full expanded width of the channel. The expanded section forced the occurrence of a hydraulic jump which at high flows encompassed the lower portion of the sloped grid. Part of the vorticity generated by the hydraulic jump was thus available to redistribute incoming litter over the full face of the

a) Plan

b) Long-section

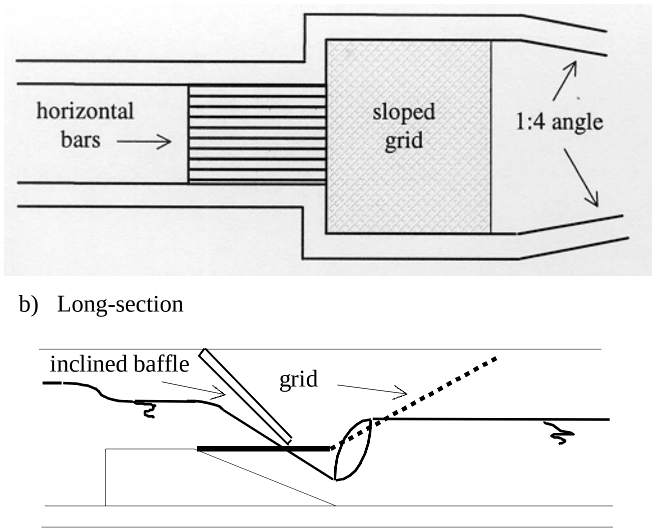

Figure 7
The Compion trap: plan and long-section

sloped grid. Downstream of the sloped grid, the walls of the channel were tapered at 1:4 so as to redirect the flow back into the original channel section with minimum head loss (Fig. 7).

The structure was extremely effective in high flows, in rapidly fluctuating flows, or in situations where, for whatever reason, the downstream water levels increased (reducing the velocities through both screens). Problems, however, arose after long periods of low flows. Particles would be deposited on the upstream side of the horizontal section to form a temporary weir. If sufficient particles were deposited in this way, they would not readily be moved and would eventually cause blockage of the section.

The tests on a uniform section were not nearly as successful as the test on the expanded section. Without the expansion, control of the hydraulic jump was lost. Without the turbulence generated by the hydraulic jump redistributing the particles on the sloped screen, both screens soon blocked.

In addition to the above, the capacity of the structure was still limited by the area of the sloped screen, although the tumbling action of the hydraulic jump generally helped to increase the depth of deposit before blockage.

Watson, 1996

Watson improved the performance of the self-cleaning screen designed by Compion by installing an inclined suspended baffle wall upstream of the horizontal screen.

The baffle wall was designed in such a way that it remained clear of the water surface except at very high flows or until such time as the horizontal screen began to block (Fig. 7). Once blockage commenced, water levels upstream were raised, forcing an increasing percentage of the flow over the blockage on the horizontal screen, under the baffle wall, and through the relatively large open area of the inclined screen (provided of course that this screen wasn't already blocked by the prior deposition of large quantities of material). The acceleration of the water through the gap between the sluice and the screen increased the shear on the deposited material to a point which was usually sufficient to induce it to move. The baffle wall also appeared to help with the packing of material on the inclined screen by increasing the downstream vorticity.

Lawson, 1997

A review of existing structures that was carried out in parallel to the laboratory investigations had shown the self-cleaning potential of declined screens (the channel flows over a screen that falls in the direction of flow). They had been used successfully on the River Pradin in France (Bouvard, 1992), in Australia (Baramy, 1997), and in South Africa (Armitage et al., 1998). There was, however, no agreement on the optimum bar shape or declination angle. Lawson therefore carried out a series of full- scale tests on screens assembled from round bars (R12), rectangular bars (10 mm wide by 30 mm deep) and a tee section (fabricated by welding together two 5 x 15 mm plates). The clearance between each bar was kept constant at 15 mm, whilst the angle of declination was varied between 0° and 45° (Fig. 8).

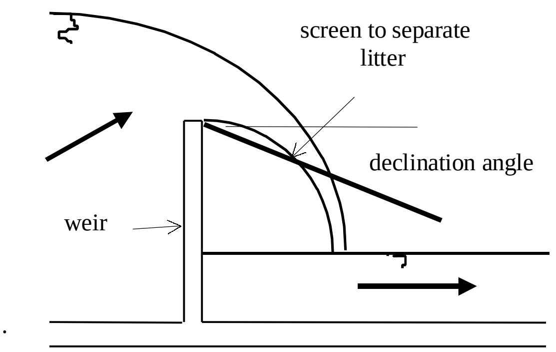

Figure 8
Long-section through the declined screen experiment

A very small declination angle resulted in the accumulation of litter on the screen and eventual blockage. If the angle of declination was increased to a certain critical minimum (different for each bar section), litter would accumulate on the screen until a combination of hydrostatic and hydrodynamic forces would induce it to slide a little. This would open a flow path through the screen upstream of the blockage. Additional material deposition and/or a change in flow rate would cause a commensurate movement of the litter along the screen until an equilibrium position was reached where litter would drop off the end of the screen at much the same rate as it was being deposited. Increasing the angle of declination further eventually resulted in the litter tumbling off the end of the screen without requiring additional deposition.

Within the experimental limits of the apparatus (screen 900 mm wide x 650 mm long, a maximum flow of 60 ℓ/s, and the litter selected - mainly full-sized polyethylene shopping bags), the critical angle of declination to ensure self-cleaning was 18° for the tee section, 20° for the round section and 22° for the rectangular section. On the other hand, the hydraulic performance - the discharge per unit length of screen - at the critical angle was significantly better for the round and rectangular sections than for the tee section at the flow rates measured. Overall, the optimum screen design (maximum flow capacity for minimum screen size and head loss) appeared to be a round bar section at about a 20° declination angle, but prototype design should be based on experimental data gathered from higher unit flow rates and a more realistic spread of litter type.

Conclusions

The only forces acting on a suspended litter particle are gravity (vertical), pressure (normal to the particle surface), shear (tangential to the particle surface), and inertia (in the direction of movement). These forces combine to cause drag (in the direction of flow), lift (normal to the direction of flow), and rotation.

If a particle touches a screen (or any other solid boundary), then two other forces may come into operation: the reaction of the boundary (normal to the contact surface), and the friction (static or kinetic) resulting from the contact (tangential to the contact surface) (Fig. 9).

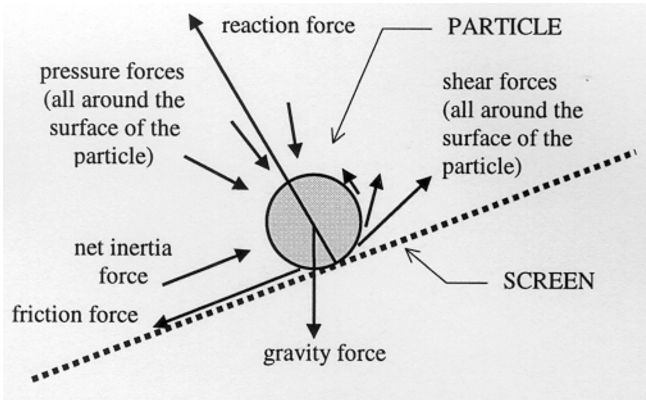

Figure 9
The forces acting on a particle in contact with a screen

If trapping and consequent blockage are to be prevented, the forces acting to free the particle must be capable of overcoming the forces acting to trap it. Pressure is related to gravity (through depth), the velocity, and the velocity gradient of the flow. Shear is directly related to the velocity and the velocity gradient of the flow. The reaction of the boundary and the friction resulting from contact are related to the gravity and velocity components normal to the boundary.

From the above it is clear that a successful litter trap design will make optimal use of the flow velocity, velocity gradient and gravity.

The investigations clearly showed that screenless or partial penetration screen traps are not viable unless there is a substantial increase in flow cross-section resulting in associated decrease in flow velocity (for example through a pond).

Screens can be made to be effectively self-cleaning if they are declined in the direction of flow and continuously subjected to a thin sheet of high velocity flow to maximise the velocity gradient and hence the shear over the screen surface (e.g. Lawson, 1997). The bar design is also important. Bars should offer as little resistance as possible to litter sliding along their surfaces, and litter that does penetrate the openings must fall free of the bars. These results show substantial agreement with those of an independent investigation carried out by Beecham and Sablatnig (1994) in Australia.

Acknowledgements

The information contained in this paper emanates from a project funded by the Water Research Commission of South Africa entitled: **The Removal of Floating and Suspended Materials from Streams** (WRC Project No. 691) and published in WRC Report

No. TT 95/98 *The Removal of Urban Litter from Stormwater Conduits and Streams*.

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